Technical Evaluation Report
Part A – Vortex Flow and High Angle of Attack

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SUMMARY

A symposium on vortex flows and high angle of attack aerodynamics for military vehicles was held in Loen, Norway from May 7 through May 11, 2001. Forty-eight papers, organized into nine sessions, addressed computational and experimental studies of vortex flows pertinent to both aircraft and maritime applications. The studies also ranged from fundamental fluids investigations to flight test results, and significant results were contributed from a broad range of countries. These papers are briefly reviewed in this report along with some synthesizing perspectives toward future vortex flow research opportunities.

1.0 INTRODUCTION

A symposium entitled Vortex Flow and High Angle of Attack was held in Loen, Norway from May 7 through May 11, 2001. The Applied Vehicle Technology Panel (AVT), under the auspices of the Research and Technology Organization (RTO), sponsored this symposium. A separate and distinct symposium (Part B – Heat Transfer and Cooling in Propulsion and Power Systems) was held concurrently.

The principal emphasis of this symposium was on "the understanding and prediction of separation-induced vortex flows and their effects on vehicle performance, stability, control, and structural design loads." It was further observed by the program committee that "separation-induced vortex flows are an important part of the design and off-design performance of conventional fighter aircraft and new conventional or unconventional manned or unmanned advanced vehicle designs (UAV's, manned aircraft, missiles, space planes, ground based vehicles, and ships)."

Vortex flows are a topic of long-standing research and, for that matter, are one of the fundamental structures of fluid mechanics. Vortices occur on multiple flow scales, and the manifestation of vortex flow effects can vary drastically among configuration classes and flow regimes. Among the many classes of vortex flows, separation-induced vortex flows are of particular interest to military vehicle aerodynamics. Due to the broad-reaching consequences of vortex flows, the predecessor organization to the RTO, AGARD, has periodically sponsored symposia to focus our understanding of separation-

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
00 MAR 2003	**N/A**	**-**

4. TITLE AND SUBTITLE	
Technical Evaluation Report, Part A - Vortex Flow and High Angle of Attack	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NATO, Research and Technology Organisation, BP 25, 7 rue Ancelle, F-92201 Neuilly-Sur-Seine Cedex, France**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Also see: ADM001490, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**26**	

induced vortex flows and their impact upon military vehicles. These prior symposia are summarized in the following table:

	Date	Location	Title	Report
o	1990	Scheveningen, The Netherlands	Vortex Flow Aerodynamics	CP-494
o	1983	Rotterdam, The Netherlands	Aerodynamics of Vortical Type Flows in Three Dimensions	CP-342
o	1978	Sandefjord, Norway	High Angle of Attack Aerodynamics	CP-247

The purpose of this paper is to provide a brief overview and synthesis of the current symposium. A total of forty-eight papers were slated for this symposium, and they were organized into nine topical sessions. An outline of this paper, which also includes the nine topical sessions, is provided below:

The original symposium program was slightly modified, and a revised program, with the symposium papers as presented, is included in Section 6.1 of this paper. Two papers, #30 and #32, were withdrawn prior to the symposium. In addition, two other papers were unavailable and were replaced with presentations (#31 and #33) of additional material from two other very extensive symposium papers. These extra presentations were consistent with the topical session and were very beneficial to the symposium.

For this review symposium papers will be cited simply by paper number, as in the preceding paragraph. Additional references will be cited with an author-date format.

2.0 GENERAL COMMENTS

There was an appropriately broad technical scope among the symposium findings. Results were presented that included fundamental fluid mechanics studies, basic configuration investigations, and full aircraft assessments. Both steady and unsteady aerodynamics were addressed. From a disciplinary perspective, results were presented from wind-tunnel experiments, Computational Fluid Dynamics (CFD) studies, and flight-test programs. Many papers addressed correlations among these disciplines. Test techniques were also addressed. In addition, results were included from both the aircraft and the maritime communities. The prior vortex flow symposia mentioned above had been focused on aircraft-motivated research, and this topical extension to include maritime results was an excellent addition to the symposium.

The technical content of the symposium was of a high caliber, and was consistent with the standard established from the prior AGARD vortex-flow symposia. Numerical sensitivities were demonstrated to be important in many of the computational results presented. Experimental uncertainty was not addressed as much, and probably needs more attention especially as regards vortex breakdown effects. There were several experimental studies that included very thorough flow analyses made possible by a suite of diverse measurements. Several commendable examples of insightful physics-based modeling can also be found among the papers.

Several hundred engineers, scientists, and technical managers attended this symposium. With regard to demographics, it was noteworthy that many career professionals in vortex flows were present along with a significant number of new contributors to this field. The final papers were available at the symposium, and all but a few papers were presented electronically.

Finally, the organization and execution of the symposium was highly professional, and the program committee, supporting staff, and hosts are to be commended for this.

3.0 OVERVIEW OF TOPICAL SESSIONS

A brief summary of each topical session is provided, followed by the overviews of the papers themselves. Prior to the topical sessions a Keynote Address was delivered.

<u>Keynote Address</u>.- D. A. LOVELL of DERA, UK presented the keynote address "Military Vortices." In this paper Mr. Lovell reviewed the wide range of vortex flows that occur on military vehicles and proceeded to classify them into three categories: (*i*) those that are desired and therefore incorporated into the vehicle design process, (*ii*) those that cannot be avoided and thus must be accommodated in a design process, and (*iii*) those that were not expected and thus were not accounted for in the design process. Vortex flow effects were discussed in the context of many current aircraft as well as submarines and future concepts. It was observed that design trends for advanced aircraft will actually increase the extent of vortex flow. At the same time, the character of these flows is different from past experience, primarily due to the advent of shaping practices for survivability. It was thus deemed essential to continue to improve our knowledge and predictive capability of these flows.

3.1 Session I: Vortical Flows on Wings and Bodies

Three papers were presented in Session I. Vortex breakdown effects were modeled for dynamic motions of a 65^o delta wing (#1) and the approach resulted in good estimation of experimental force and moment properties. Next, detailed flow field measurements were reported from a water tunnel experiment (#2) for both a 65^o and a 55^o delta wing and sweep effects were discussed. Finally, high angle-of-attack missile aerodynamics at supersonic speeds were reported for both round and square body cross sections (#3). Reasonable correlations with parabolized Navier-Stokes calculations were included.

Paper 1.- X. Z. HUANG presented research co-authored with E. S. HANFF of the Institute for Aerospace Research, National Research Council, **Canada**. This effort was focused on modeling the vortex breakdown location over a 65^o delta wing for various dynamic motions. Experimental results were included from the IAR 6x9 foot wind tunnel, the USAF 7x10 foot wind tunnel, and the IAR 15x20 inch water tunnel. Rolling, pitching, and coning motions were investigated. A key result for this paper was a modeling approach to predict the vortex breakdown location. The basic approach was based on a nonlinear indicial response method coupled with a nonlinear formulation as proposed by Tobak and Schiff (1981). It was shown that the vortex breakdown location could be approximated by the superposition of three convolution integrals of certain response functions in a way that captures nonlinear effects. Very accurate estimates by this technique were demonstrated for a rolling motion, and the authors stated that similar procedures could be used for the other motions of interest.

Paper 2.- M. V. OL presented research from the Air Force Research Laboratory, Wright Patterson, **USA**. This effort was an experimental investigation of detailed flow-field properties for a 55^o and a 65^o delta wing as obtained in a water tunnel. The principal measurements were obtained with stereoscopic digital particle image velocimetry, which allows for an instantaneous snapshot of the data in a given plane. This measurement feature was exploited so that unsteady attributes of the vortex flow could be measured. Flow visualization was also used to track the basic leading-edge vortex core trajectories and breakdown properties including unsteady effects. The flow-field data presented would be very useful for CFD calibration purposes. It was also very instructive to include a lower-sweep wing in this vortex flow investigation. Additional insight could be gained by analyzing these data in terms of similarity parameters, such as given by Smith (1966) for conical flow (e.g., $a=\sin\alpha/\tan\gamma$, where γ is the wing semi-apex angle) or developed by Hemsch and Luckring (1990) for delta wings.

Paper 3.- S. A. PRINCE presented research co-authored with T. J. BIRCH and G. M. SIMPSON of DERA, Bedford, **UK**. This effort was focused on supersonic missile aerodynamics. The geometries had either a square or circular cross-section, a 3-calibre nose and a 10-calibre body. Experimental results were presented from the DERA Bedford High Supersonic Speed Tunnel and computational results were also shown from an iterative Parabolized Navier-Stokes (PNS) solver. Results were shown for Mach 2.5 and 4.5 and for various roll orientations of the square-cross-sectioned body. Good predictions of normal force and center of pressure were shown. The PNS code also was shown to provide good qualitative agreement with the measured off-body flow structures for the circular cross-section body. Off-body flow structures from the PNS code were shown for the square-cross-section body at various roll angles but were not correlated with experiment. The predicted side force and yawing moment for these roll-orientation cases compared fairly well with experiment.

3.2 Session II: Experimental Techniques for Vortical Flows

Five papers were presented in Session II. Two of these were focused primarily on experimental results, in one case for a generic forebody (#4), in the other for a double delta wing (#7). A basic analysis of the flow near vortex cores (#5) demonstrated fundamental limitations for nonintrusive measurement techniques that rely on seeded flow. A pressure sensitive paint technology capable of unsteady flow measurements was presented (#6) and results shown for a cropped delta wing rolling at 10 Hz. Finally, an overview was presented of our vortex flow knowledge for slender delta wings (#8), and a new collaborative effort was proposed to resolve a number of the remaining gaps in this understanding.

Paper 4.- D. K. PANTELATOS presented research co-authored with D. S. MATHIOULAKIS of the National Technical University, **Greece**. In this effort a hemisphere-cylinder was tested at low speeds in a subsonic tunnel at the Aerodynamics Laboratory of the National Technical University of Athens. Static surface pressure measurements and surface flow visualization via an oil-dot technique were obtained. Because of the forebody bluntness very few asymmetries were captured in these measurements. Both circumferential as well as longitudinal pressure distributions were shown.

Paper 5.- D. I. GREENWELL presented this research from DERA Farnborough, **UK**. In this paper the author presented a very insightful analysis of flow visualization attributes with an emphasis on the flow near the core of leading-edge vortices at typical wind tunnel conditions. He used the conical vortex flow governing equations of Hall (1961) and accounted for drag and body force effects of tracer particles in this flowfield. His results matched experimental observation very well, and demonstrated that any particle will depart significantly from the local velocity field in the vortex core. This presents a fundamental dilemma, at least at wind-tunnel model scales, to all flowfield measurement techniques that require seeding of any sort for measuring detailed flow properties within the core of a leading-edge vortex. It appears that alternate seedless technologies (laser-induced thermal acoustics as described by Hart (2001) would be one example) need to be developed for these non-intrusive measurements. The author also presented analyses of burst vortex flowfields that once again addressed seeding influences on observed patterns and also related these patterns to some of the fundamental breakdown "types" observed by Mezic et. al. (1998).

Paper 6.- This research was presented by R. ENGLER and co-authored with S. FONOV, C. KLEIN, K-A. BUETEFISCH, and D. WEISKAT of the German Aerospace Center, DLR Goettingen; K-W. BOCK of the German-Dutch Wind Tunnels, and W. FRITZ of EADS, **Germany**. This effort was an experimental investigation of the unsteady aerodynamics of a cropped 65^o delta wing as measured using pressure sensitive paints. The experiment was performed in the transonic 1m x 1m tunnel DNW-TWG in Goettingen. Results were presented for a Mach number of 0.8, two angles of attack, and for the model rolling about the body axis at 10 Hz. The unsteady pressure sensitive paint system had a relatively fast response, and the results were anchored with several Kulite measurements. A comparison to Euler computations showed fair correlation, although many details differed between the experimental and the computational results.

Paper 7.- A. M. CUNNINGHAM of the Lockheed Martin Aeronautics Company, **USA**, presented this research that was co-authored with E.G.M. GEURTS of the National Aerospace Research Laboratory, **The Netherlands**. Dr. Cunningham presented an overview of an extensive test program for a strake/cropped-delta wing configuration at transonic conditions. These tests were conducted at the NLR High-Speed Wind Tunnel (HST) with several entries from 1992 to 1996. The measurements included transonic forces and moments, pressures, and flow visualization. Both steady and unsteady results were obtained, and the results included hysteresis loops. The tests have provided an extensive database for high angle-of-attack flows with multiple vortices and shocks. The flow visualization data were shown to be useful for linking flow field structures to the other aerodynamic measurements. This work has been included in the RTO database for computational Validation and Verification.

Paper 8.- D. HUMMEL, of the Technical University of Braunschweig, presented this research that was co-authored with G. REDEKER of the DLR, **Germany**. Dr. Hummel summarized much of the knowledge of slender delta wing vortex flows. In addition to the primary vortex, interference mechanisms with the secondary vortex and vortex breakdown were discussed. Experimental and computational results were presented from a broad range of sources that included the International Vortex Flow Experiment (VFE-1), TU Braunschweig, ONERA, NASA, and others. Despite considerable progress, there remain a number of information gaps that inhibit our fundamental understanding of this flow, and Dr. Hummel proposed a new international collaboration on vortex flows, dubbed VFE-2, which could address many of the remaining questions for this flow. A brief review of experimental techniques pertinent to vortex flows was also presented.

3.3 Session III: Numerical Simulations of Vortical Flows

Seven papers were presented in Session III. The first paper (#9) addressed low-speed design issues for supersonic transport class wings and demonstrated the utility of leading-edge suction as a design parameter. From a topical standpoint, this work was more similar to the other papers presented in Session 9 on Vehicle Design. Unsteady aerodynamic computations based upon a panel method (#10) modeled wake roll-up for dynamic wing motions and was shown to provide good qualitative wake predictions with relatively minimal computational resource requirements.

The remaining five papers addressed Euler and Navier-Stokes applications to vortex flows. In two dimensions the time-accurate passage of a vortex over an airfoil was simulated with a Navier-Stokes method (#12). Careful numerical assessments showed significant turbulence modeling effects for the vortex flow about a 65^o delta wing (#14). Steady and unsteady Euler computations were compared with experiment for a 65^o delta wing at transonic speeds as part of a multinational collaboration (#11). A new capability to compute vortex flows with an adaptive unstructured Navier-Stokes method demonstrated significant improvements in solution quality and data correlation (#13).

Imbedded meshes were shown to provide good Navier-Stokes predictions for missile aerodynamics (#15).

Paper 9.- R. K. NANGIA of Nangia Aero Res. Associates, presented this research that was co-authored with A.S. MILLER, BAe Systems Airbus, **UK**. The focus of this work was on some of the lower-speed aerodynamic design challenges of supersonic transport wings. These wings are primarily designed for efficient supersonic cruise, and this presents a number of unique design challenges for subsonic and transonic performance that often include separation-induced leading-edge vortex flow effects. Dr. Nangia addressed the control and suppression of the vortex flow with different types of leading and trailing edge devices. He also demonstrated very effective use of the attainable leading-edge thrust theory of Carlson (1985) for the analysis and design of these wings. Although presented in this session, Dr. Nangia's research was more similar to the papers presented in Session IX on Vehicle Design.

Paper 10.- A. LEROY presented this research that was co-authored with F. BURON and P. DEVINANT, University of Orleans, **France**. Dr. Leroy presented results from a fairly classical panel method approach (Green's theorem) for computing nonlinear time-dependent flows of wings with variable geometry and arbitrary motion. Emphasis was placed upon wake roll-up features, and examples were presented for (i) a flapping variable geometry wing of moderate aspect ratio and for (ii) an oscillating low aspect ratio wing. With this formulation, wake vorticity is inherently preserved as contrasted to most CFD methods that can suffer extensive numerical dissipation of the wake vorticity. Dr. Leroy's results demonstrated the power and efficiency of this approach for computing these complex time-dependent flows.

Paper 11.- This research was presented by W. FRITZ of EADS, **Germany**, and co-authored by M.T. ARTHUR of DERA, **UK**, F.J. BRANDSMA of the NLR, **The Netherlands**, K.A. BUETEFISCH of the DLR, **Germany**, and N. CERESOLA of Alenia, **Italy**. This paper summarized a well-coordinated experimental and numerical investigation of the unsteady aerodynamics for a cropped 65^{o} delta wing. The wing was rolling steadily about its body axis at high angle of attack and transonic speeds, and hence the angle of attack and angle of sideslip were varying periodically. Calculations were achieved for a broad range of Euler methods by dispersing the work among the many participants. Correlation with experiment was reasonable for steady flow and not as good for the unsteady case. The experimental results were again achieved with pressure sensitive paint, although less detail of the experimental methodology was presented here than was the case in Paper #6 of this symposium. Nonetheless, the work reported in this paper is an excellent example of effective collaboration.

Paper 12.- M. MAMOU presented this research co-authored with H. XU and M. KHALID of the National Research Council, **Canada**. Dr. Mamou presented results from a two-dimensional Navier-Stokes simulation of a vortex passing over an airfoil. The time-accurate computations simulated the passage of a shock over two airfoils, one downstream of the other. The starting vortex from the upstream airfoil then convected over the downstream one to set up the subject flow. Numerical diffusion of the vortex was curtailed through the use of an imbedded fine grid in the region of the vortex trajectory. Results from this complex flow simulation seemed plausible although no correlation with experiment was presented.

Paper 13.- S. Z. PIRZADEH presented this research from NASA Langley, **USA**. In this paper Dr. Pirzadeh presented some exceptional computational results for a new adaptive-grid unstructured Navier-Stokes methodology. With this technique, cells adapt and cluster in the vicinity of the vortex, thereby providing greatly enhance resolution for the high flow gradients therein. Sufficient grid resolution is retained elsewhere, such as on the wing surface, and as a consequence significantly improved correlation with experiment was demonstrated with this method for a blunt-edged 65^o delta wing tested at NASA Langley. Good correlation was also shown for a more complex chine-forebody/wing/tail configuration at conditions conducive to vortex breakdown. This adaptive capability appears to be very important for grid resolving the off-body vortex flow physics within practical computational resource limitations.

Paper 14.- F. J. BRANDSMA presented this research that was co-authored with J. C. KOK, H. S. DOL, and A. ELSENAAR of the NLR, **The Netherlands**. Dr. Brandsma presented some careful computations for a cropped 65^o delta wing and showed significant consequences of the turbulence model in capturing vortical structures. In this work the k-ω model was assessed along with two variants, and the modified forms were shown to significantly improve the vortex flow simulation both in terms of the vortex core flow as well as induced effects on the wing surface. These type of detailed results are most useful from a CFD uncertainty perspective, and demonstrate why care needs to be taken in computing vortex flows with CFD as regards turbulence modeling.

Paper 15.- H. BROUSSARD of Matra BAe Dynamics presented this research that was co-authored with P. CHAMPIGNY and P. d'ÉSPINEY of ONERA, M. BREDIF of Matra BAe Dynamics, and J. P. GILLYBOEUF and Y. KERGARAVAT of EADS-Aerospatiale Matra Missiles, **France**. This work was directed at establishing a more routine Navier-Stokes capability for external missile aerodynamics applications. The multiblock method incorporated overlapping adaptive meshes for the vortices, and results were shown for three turbulence models and a number of configurations. Good correlation was achieved for a transonic application, and reasonable correlation for a supersonic case. Overall, this work demonstrated an effective relationship between code development and code transfer to industry.

3.4 Session IV: Vortex Stability and Breakdown

Eight papers were presented in Session IV. Vortex breakdown continues to be crucial phenomenon to understand. A number of carefully executed numerical investigations with the Navier-Stokes equations provided insight to vortex breakdown for Burgers vortex (#16) and for a vortex/normal-shock interaction (#18). Numerical factors affecting solution quality for high incidence flow about delta wings (#22, #23) and a Mirage-2000 class of wing (#23) were also carefully assessed. A survey of a large number of data sets for vortex breakdown (#17) demonstrated that there are many inconsistencies. This indicates a need for validation data sets from new experiments designed to incorporate rigorous experimental uncertainty practices. Manipulation of vortex breakdown on a delta wing by surface blowing (#19, #20) was demonstrated both with numerical and experimental results and included test technique development. The ability to use complex variables for predicting vortex-sheet instabilities (#21) was demonstrated using only meager numerical resources.

Paper 16.- D. L. DARMOFAL of MIT presented this research that was co-authored with A.W. CARY of Washington University (St Louis), **USA**. The paper reports a very careful computational study of vortex breakdown for Burgers vortex. Their results demonstrated that the onset of axisymmetric vortex breakdown for the subject vortex corresponded to a condition of local criticality as determined from a local eigenvalue problem. Weak asymmetric disturbances to a steady axisymmetric base flow were also studied and found to grow once the base flow itself achieved a critical state leading to axisymmetric breakdown.

Paper 17.- This research was presented by C. E. JOBE of the Air Force Research Laboratory, **USA**, and was co-authored with X. Z. HUANG and E. S. HANFF of the National Research Council of **Canada**. Dr. Jobe reported on a critical analysis of over sixty experiments with regard to vortex breakdown location over 65^o and 70^o delta wings. It was shown that there is considerable uncertainty in the progression of the burst location over the delta wing as angle of attack is increased due to a number of experimental conditions that have either not been carefully controlled or even reported. Examples included tunnel blockage effects, model support interference, static aeroelastic deformation of the model, and model beveling effects used to achieve the sharp leading and trailing edges. Additional uncertainty has been found even with respect to how the burst location itself is defined. This was a very useful analysis of existing data sets, and demonstrated one of the needs for additional experimentation regarding vortex breakdown.

Paper 18.- O. THOMER presented this research that was co-authored with E. KRAUSE and W. SCHROEDER of RWTH Aachen, **Germany**. Mr. Thomer used the Euler and Navier-Stoke equations to simulate the interaction of a longitudinal free Burgers vortex with a normal shock wave. The initial condition for vortex circulation was varied such that vortex breakdown developed among the cases included in the study. These very careful computations included a detailed view of the flow within the breakdown bubble and the effects of viscosity (as contrasted to the inviscid simulation) were presented. A breakdown criterion was also developed that correlated well with computational and experimental findings.

Paper 19.- P. MOLTON of ONERA, **France** presented this research that was co-authored with A. MITCHELL of the USAF Academy, **USA**, and D. BARBERIS, D. AFCHAIN, O. RODRIGEZ, and J. PRUVOST of ONERA, **France**. The effects of fluid injection on vortex breakdown over delta wings were investigated at low speeds in two separate experiments. The first experiment was conducted in the ONERA F2 tunnel with a 70^o delta wing equipped for upper surface blowing roughly along the vortex core trajectory. Breakdown location was determined from off-body laser light sheet visualization as well as by inference from unsteady pressure measurements on the wing upper surface, and repeat measurements were performed that demonstrated some of the uncertainty in quantifying the vortex breakdown location. Both steady and pulsed blowing were assessed and resulted in downstream movement of the burst point. The second experiment was conducted in a water tunnel with a 60^o delta wing equipped with a variety of upper surface blowing nozzles. Both flow visualization and force/moment data were obtained from the water tunnel and again showed a delay in breakdown effects due to flow injection.

Paper 20.- This research was presented by both A. MITCHELL and S. MORTON of the USAF Academy, **USA**, and co-authored with P. MOLTON of ONERA, **France**, and Y. GUY of Israeli Armament, **Israel**. Here again the effects of fluid injection on vortex breakdown over delta wings were investigated at low speeds in two separate experiments. Computations were also performed for the second experiment. The first experiment was conducted in the ONERA F2 tunnel with the 70^o delta wing and tangential upper surface blowing described in Paper #19. Upper surface blowing (also referred to as "along-the-core" blowing) was assessed for various mass-flow injection rates. Laser Doppler Velocimetry (LDV) measurements were performed to quantify the breakdown location and flow properties, and the blowing was effective in displacing the burst point downstream. The second experiment addressed periodic leading-edge blowing/suction with a net mass flux of zero for a 70^o delta wing. The test was performed in the US Air-Force Academy water tunnel, and the results demonstrated extensive effects on the vortex trajectory and wing aerodynamics from this type of blowing. For the Navier-Stokes calculations considerable attention was paid to numerical uncertainty (e.g., grid resolution, time step considerations, etc.) and the resultant computations were shown to provide a good simulation of the experimental findings.

Paper 21.- M. MOKRY of the National Research Council, **Canada** presented results of a study that was focused on the numerical modeling of vortex instabilities and interactions through the use of complex variable techniques. Dr. Morky showed a variety of examples for the development and growth of sub-scale vortex instabilities on vortex sheets. The results demonstrated that this class of shear layer instability can be assessed with fundamental theoretical modeling and very modest computational resources.

Paper 22.- This research was presented by S. GOERZ and Y. LE MOIGNE and co-authored with A. RIZZI of the KTH Royal Institute of Technology, **Sweden**. The first portion of this work was directed at the application of a multiblock Navier-Stokes code to predict the steady vortex flow over a 70^o delta wing at a high angle of attack of 35^o. Considerable attention was paid to computational uncertainty associated with the effects of grid topology and refinement as well as other numerical parameters. A second configuration with a 63^o cropped delta wing and a body was also studied. A number of significant influences due to the mesh were shown, and for this study an H-H mesh was found to be most suitable overall. A second study of the unsteady aerodynamics for the same 70^o delta wing pitching in a sinusoidal motion was presented for both inviscid and laminar flow solutions. Overall agreement with experiment was good, and the results showed plausible effects of viscosity and vortex breakdown as regards force and moment hysteresis loops.

Paper 23.- J-P. ROSENBLUM presented this research that was co-authored with J-M. HASHOLDER and J-C. COURTY of Dassault Aviation, **France**. This work was directed at obtaining Euler and Navier-Stokes predictions of vortex breakdown effects about the Mirage 2000 60^o cropped delta wing with a generic fuselage representation. An unstructured solver was used in order to represent deflected leading edge devices with attendant gaps and breaks. Initial results for what appeared to be a very reasonable grid were shown to be inadequate, and greatly improved results were achieved through mesh refinement and utilization of an extended turbulence model. Further refinement studies were performed with a 70^{o} delta wing, and among other things mesh refinement was shown to significantly effect the flow simulation in the core of the vortex and thus also significantly affect vortex breakdown.

3.5 Session V: Vortex Flows in Maritime Applications

Six papers were presented in Session V and one paper was withdrawn. The maritime research was an excellent extension to this vortex flow community that has traditionally had an aircraft focus. Many vortex-dominated problems were presented in an overview (#24) as well as in the subsequent papers. Wind-over-deck flows were simulated with Navier-Stokes methods (#25, #26) and time-accurate computations of this complex flow were shown to match full-scale ship measurements reasonably well. Submarine roll excursions were explained from a stability analysis of experimental data (#27), and advanced Navier-Stokes computations were presented for both submarines (#29) and torpedoes (#28). The maritime work demonstrated a very strong connection between fleet issues and the research activities reported.

Paper 24.- J. J. GORSKI of the Naval Surface Warfare Center, **USA** presented a very good overview of maritime vortices and the status of computing these flows. The work showed very strong ties between customer needs and research activities. For surface ships the hull vortices were shown to be very important, especially as regards the inflow to the propulsor. CFD has been used to assess scale effects for Reynolds numbers ranging from 12 million to 500 million, although for this maritime application surface roughness can be an issue for this scaling. It was pointed out that future trends in ship design would make vortices even more of an issue than they are today. Submarines were also discussed, and for these vessels design issues are more sensitive because the hull is already such a clean surface. Vortices shed from the submarine appendages can have crucial effects on performance. A variety of Reynolds-averaged Navier-Stokes applications were shown which also demonstrate rapid advancement of this technology for maritime use.

Paper 25.- S. A. POLSKY presented this research that was co-authored with C.W.S. BRUNER of the Naval Air Warfare Centre, **USA**. Computations were performed to simulate the unsteady air wake over ship upper surfaces. This separated wake can include many vortices shed from the superstructure and other edges of the ship geometry. Because aircraft must take off and land in this unsteady flow, it is of great interest to predict and eventually control it. Unstructured grids were used to model much of the complex geometry for an actual ship, and the flow was solved with a Navier-Stokes technique. The CFD was initially calibrated with wind tunnel data, and then time-accurate computations were performed to simulate the subject flow. The unsteady calculations were averaged the same way that full-scale experimental measurements were averaged, and the correlation was good. As a numerical study, "steady-state" solutions were also generated and demonstrated much poorer correlation with measurement as would be expected. From this work it seemed compelling that the unsteady formulation was vital for achieving a reasonable correlation with full-scale ship data. This work is a very promising first step toward simulating a very complex and important flow.

Paper 26.- The research presented by C. T. TAI of the US Naval Surface Warfare Centre, **USA** also addressed ship air-wake simulations. The geometry for this study was a very simple and generic representation of a ship, and the computations were performed with a structured-grid Navier-Stokes code. Steady-state solutions were obtained and showed a separated flow over the aft portion of the geometry. There were, however, no correlations with experiment nor was there any discussion justifying the steady-flow approximation for this particular application.

Paper 27.- G. D. WATT of the Defence Research Establishment Atlantic, **Canada** presented research that was directed at a quasi-steady evaluation of submarine rising stability. During a limited and controlled emergency rise a submarine can exhibit a roll instability that was shown to be associated with a destabilizing hydrodynamic rolling moment on the sail. Tests were conducted in the IAR 1.5m and 9m tunnels to obtain data up to very high incidences and a thorough analysis of these data was summarized. A stability analysis was also presented to demonstrate the link between the excursion and the aforementioned destabilizing hydrodynamic rolling moment. This work demonstrated an excellent linkage of the research topic to actual fleet issues.

Paper 28.- This research was presented by P. L. LYES of BAe Systems and was co-authored with P. STEER of DERA, **UK**. The vortex effects for the forces and moments of underwater weapons were studied computationally with a blocked structured-grid Navier-Stokes solver. Turbulence was accounted for with a k-ε model combined with wall functions. The geometric representation for this torpedo was quite complete and included the duct, fins, rotor, stator, and rudders. Force and moment comparisons with experimental wind tunnel results for yawed flow were very encouraging.

Paper 29.- This research was presented by K. SREENIVAS and co-authored by D. HYAMS, X. WANG, B. MITCHELL, L. TAYLOR, D. L. WHITFIELD of the Computational Simulation and Design Centre, **USA**. The role of grid resolution and Reynolds number scale effects were studied for a notional submarine geometry with an unstructured Navier-Stokes code. The configuration included a representative hull and sail, and calculations were shown for typical model scale, quarter scale, and full scale Reynolds number conditions. A good correlation with model scale data was shown, and significant grid resolution and scale effects were also discussed. Some full-scale Reynolds number flow features were absent at model scale conditions, and hence simple Reynolds number scaling would not account for any effects of these high Reynolds number flow structures.

Paper 30.- This paper was withdrawn.

3.6 Session VI: Vortex Interactions and Control

Six papers were presented in Session VI. Paper 32 had been withdrawn, and the original Papers 31 and 33 were not available for the Symposium; both of these were replaced with other available presentations. Co-rotating vortices were discussed for one configuration where the flow is expected (a double delta wing, #33) and two other configurations where the flow was not anticipated (the F-106B aircraft, #31, and an advanced UCAV concept, #34). All of these studies were experimental and used advanced measurement techniques. Vertical tail buffet due to vortex interaction was significantly reduced through the use of an active auxiliary rudder system (#35). Geophysical vortices were modeled for wind/mountain interactions with the Euler equations and were shown to be a probable cause of an in-flight helicopter mishap (#36). The combined use of analytical and numerical techniques showed very good simulation of cavity flows and store separation (#37). This analysis was accomplished at a fraction of the cost of Navier-Stokes computations.

Paper 31.- This research was presented by J. E. LAMAR of NASA Langley, **USA**. Vapor screen in-flight flow visualization methodology was reviewed in this presentation. The work came from a flight test program with an F-106B aircraft to assess the vortex flap concept. In addition to discussing many operational aspects of this class of testing, a sampling of the aerodynamic findings from this research was presented. This included correlations between surface flow and off-body flow patterns, in-flight Reynolds number effects, and in-flight discovery of multiple vortex systems. Good correlation of flight and wind tunnel data was also presented. The text for this presentation is included with Paper #43 of this conference authored by Brandon, Hallissy, Brown, and Lamar. (The originally accepted Paper 31 by another author had to be withdrawn.)

Paper 32.- This paper was withdrawn.

Paper 33.- H. A. GONZALEZ of the Naval Air Systems Command presented this research that was co-authored with G. E. ERICKSON of NASA Langley and B. G. MCLACHLAN and J. H. BELL of NASA Ames, **USA**. Experimental results for a $76^o/40^o$ double delta wing were presented from a subsonic test conducted in the NASA Langley 7x10-foot tunnel. The data presented included static surface pressures, pressure sensitive paint, six-component forces and moments, and laser-light-sheet off body vortex-flow visualization. Experimental data repeatability was also addressed. Vortex interactions from a double delta wing can be complex, and this very thorough use of data technologies provided a most insightful understanding of the subject flow. The text for this presentation is included with Mr. Gonzalez' other paper in this conference, Paper #48. (The originally accepted Paper 33 by another author had to be withdrawn.)

Paper 34.- T. A. GHEE presented this research that was co-authored with D. R. HALL, Naval Air Systems Command, **USA**. Low-speed vortex shedding effects for an Uninhabited Combat Air Vehicle (UCAV) concept were explored experimentally in the Naval Aerodynamic Test Facility. This class of vehicle can exhibit some challenging vortex flow effects due to the moderate sweep (approximately 48^o) and small leading-edge radii incorporated for survivability. Here again, a very thorough suite of measurement technologies was used to gain understanding of this flow. Measurements included six-component forces and moments, surface fluorescent oil flows, static and dynamic surface pressures, hot-wire flow field data, and laser-vapor-screen off-body flow visualization. Some preliminary unstructured grid Navier-Stokes computations were also performed. Both the experimental and computational results showed a multiple vortex system being generated from the constant-sweep leading edge.

Paper 35.- This research was presented by G. BREITSAMTER of the Technical University of Muenchen, **Germany**. Vertical tail buffet alleviation was demonstrated experimentally through the use of an active auxiliary rudder system. Tests were conducted with a model representative of the Euro-Fighter 2000 in the low-speed Tunnel B at TU-Muenchen. High angle-of-attack tail buffet occurred due to unsteady wake flows and burst vortex flows that could have arisen from either the wing or the canard. A number of different fin buffet metrics were assessed, and all showed significant reduction by the technique employed. As one example, the first fin bending and first fin torsion spectral density peaks were reduced by as much as 60 percent up to angles of attack of 30^o. Anticipated further improvements for this technique were also discussed.

Paper 36.- H. NOERSTRUD of the University of Trondheim presented this research that was co-authored with A. OESTMAN of CFD Norway, **Norway**. An Euler simulation was performed to model the interaction of wind flows and local topography for a region surrounding the Straumsfjorden in northern Norway. This work was part of an incident investigation of a rescue helicopter that had encountered a sudden and extreme pitch down during an emergency flight. The helicopter was safely landed but had lost the entire horizontal stabilizer. The Euler simulation showed that steady winds could interact with the local topography so as to form strong vortical flow patterns in the vicinity of the incident. It was further observed that the resultant induced flow field could account for the subject helicopter behavior.

Paper 37.- N. MALMUTH of the Rockwell Science Center presented this research that was co-authored with J. COLE of the Rensselaer Polytechnic Institute, **USA**, A. FEDEROV and V. SHALAEV of the Moscow Institute of Physics, **Russia**, and M. HITES and D. WILLIAMS of the Illinois Institute of Technology, **USA**. Aerodynamic theory was used to facilitate analysis of the computationally intensive flow field associated with store separation from a cavity. This theoretically anchored approach exploits asymptotic analysis to reduce numerical requirements and produced useful results in minutes on a PC that are comparable to CFD results that required approximately 15 hours on a supercomputer. Correlation with experiment demonstrated that this approach can produce very useful estimates for the store release problem at low speeds, and the method is being extended to transonic flows.

3.7 Session VII: Vortex Dynamics

Three papers were presented in Session VII. Delta wing force and moment hysteresis effects were modeled very effectively through the use of the suction analogy and neural networks (#38). Low-speed flows for forebodies rotating about the wind axis at a high angle of attack were predicted well with Navier-Stokes computations (#39). This work also involved numerical sensitivity assessments. Experimental research for vortex flows about micro-air vehicles was also shown (#40).

Paper 38.- This research was presented by L. PLANCKAERT of ONERA, **France**. Unsteady aerodynamic coefficients for a delta wing at high incidence were modeled by two different techniques. These flows are dominated by leading-edge vortices and include near-field vortex breakdown and hysteresis effects. The basic approach was to represent phenomenology of the flow, then select tools to build an appropriate model. One approach was somewhat traditional and used transfer functions to model unsteady effects. The other approach used a variant of the Polhamus (1966) suction analogy due to

Goman and Khrabrov (1992) to approximate vortex breakdown effects. This second approach captured the vortex flow physics better and yielded improved correlation with experiment. The approach was then coupled with a neural net to produce an exceptional model of force and moment hysteresis effects for angles of attack ranging from -20^{o} to 90^{o}.

Paper 39.- C. P. VAN DAM presented this research that was co-authored with S. SAEPHAN, University of California, C. M. FREMAUX of NASA Langley, and T. DALBELLO of NASA Glenn, **USA**. Navier-Stokes computations were performed for two smooth-sided forebodies at high-angle-of-attack rotary conditions. The bodies had a two-diameter ogival forebody and had either a circular or rounded square cross section. Low speed data were obtained in the DERA 13x9 foot tunnel (Bedford) and the DERA 8x6 foot tunnel (Farnborough). Three turbulence models were assessed along with other numerical features of the flow solver, and low speed results were shown for 60^{o} angle of attack and a normalized rotary rate about the wind axis of $\Omega b/2U = 0.2$. Although force and moment comparisons were not made, the computed and experimental pressures matched well for multiple stations on the ogival forebody.

Paper 40.- M. F. PLATZER presented this research that was co-authored with K. D. JONES, Naval Postgraduate School, **USA**. This work explored the use of vortex flows for micro-air and sea propulsion. A review of vortex structures generated by flapping airfoils was followed by discussion of vortex interactions for multiple airfoils with various dynamic motions. Finally, flapping finite-span wings were studied and a comparison shown of unsteady wake trajectories for a low-speed experiment and predictions from a panel code with discrete wake roll-up modeling.

3.8 Session VIII: Flight Testing

Five papers were presented in Session VIII. All of these papers addressed vortex-dominated flows. An overview of the X-31 program (#41) demonstrated this to be a very clearly focused and cost-effective research activity for post-stall maneuver aerodynamics. A second paper about the X-31 (#42) focused primarily on the forebody flow effects for high angle-of-attack yawing moments. In-flight flow visualization for the F-106B-vortex flap experiment (#43) demonstrated that the vortex flap vortex flow differed from the design objective due to small geometric perturbations. There was, however, no significant performance degradation. Flight tests with the F-16XL-1 (#44) resulted in a very extensive suite of measurements for the vortex flow generated by this cranked arrow wing. Finally, flight tests with the F-18 HARV (#45) demonstrated that forebody actuated strakes could provide significant yawing moment control at high angles of attack.

Paper 41.- H. ROSS of EADS Military Aircraft, **Germany** presented this research. A thorough overview was presented of the X-31 program history and achievements. The X-31 program goal was clearly focused on post stall maneuver for tactical use. This flow regime, of course, has very prominent vortex flow effects. The program was accomplished with two relatively low-cost research vehicles, and is an excellent example of effective multinational collaboration. Follow on research possibilities were also discussed.

Paper 42.- This research was presented by B. R. COBLEIGH of NASA Dryden and co-authored with M. A. CROOM of NASA Langley, **USA**. The X-31 static and dynamic yawing moments were analyzed through high angle-of-attack conditions including comparisons between flight and ground-based measurements. The primary source of these yawing moments is asymmetric forebody separation, and results were discussed for the basic X-31 forebody as well as several forebody modifications. Both wind tunnel and water tunnel data were used to gain understanding of the subject forebody flows.

Paper 43.- This research was presented by J. M. BRANDON and co-authored with J. B. HALLISSY, P. W. BROWN, and J. E. LAMAR of NASA Langley, **USA**. In-flight flow visualization results were presented for the F-106B research aircraft fitted with vortex flaps. Results were presented for angles of attack from 9^o to 18^o and Mach numbers from 0.3 to 0.9. Both surface flow visualization and off-body flow visualization data were used to understand the vortex flow for this particular vortex flap application. The flap was designed to generate a single leading-edge vortex for the design conditions, but it was discovered in flight that multiple co-rotating vortices developed. The source of these vortices was traced to small geometric irregularities in the leading edge and this was confirmed with subsequent wind tunnel testing. Despite this drastic difference in the vortex flow structure, either flow produced about the same performance benefit.

Paper 44.- J. E. LAMAR of NASA Langley, **USA** presented this research. The F-16XL-1 aircraft was used to obtain an extensive suite of in-flight flow measurements over a range of conditions exhibiting vortex flows. The measurement devices included static surface pressures, hot films, boundary-layer rakes, Preston tubes, and surface-tuft flow visualization. Data were obtained from low speed to transonic conditions, and it is rare that such an extensive suite of measurements is realized. Blocked-grid Navier-Stokes computations were also performed and compared with selected flight results. A number of good correlations between CFD and flight were shown, including surface pressure coefficients, vortex trajectories, and some local boundary-layer properties. Portions of this data set are also being made available through the world wide web.

Paper 45.- This research was presented by D. F. FISHER of NASA Dryden and co-authored with D. G. MURRI of NASA Langley, **USA**. Both wind-tunnel and flight-test results were presented for actuated forebody strakes that were implemented on the F-18 High Angle of Attack Research Vehicle. The strakes were demonstrated to provide extensive yaw control at high angles of attack where conventional rudders have, for the most part, lost effectiveness. Good ground-to-flight correlations of the forebody-induced yawing moments were shown. In addition, forebody surface pressures and flow visualization obtained in flight were used to provide very good understanding of the vortex flow effects on the subject forebody aerodynamics.

3.9 Session IX: Vehicle Design

Three papers were presented in Session IX. An overview of a recent RTO Symposium was presented (#46) with an emphasis on active vortex control. This review was a very effective leverage of the information from one RTO Symposium for the participants of the present one. Next, Euler methods were shown to be sufficiently fast and accurate for application to the preliminary design activities of advanced fighter concepts (#47).

Emphasis was on force and moment properties for configurations with edge-generated vortices. Finally, experimental effects were presented for fillet shaping at the sweep discontinuity for a double delta wing (#48). A very thorough understanding of the resultant vortex flow was achieved through the use of a robust suite of test techniques.

Paper 46.- This research was presented by D. J. MOORHOUSE of the Air Force Research Laboratory, WPAFB, **USA**. A focused review was presented from the RTO symposium entitled "Active Control for Enhanced Performance Operational Capabilities of Military Aircraft, Land Vehicles and Sea Vehicles," held in Braunschweig Germany on May 8-11, 2000. Dr. Moorhouse's emphasis from this symposium was on design issues associated with full-scale application of active control of vortex flows. Increased efforts in modeling and simulation were discussed and recommended as a means to reduce unanticipated characteristics encountered in flight. Active vortex control could play a key role in addressing these characteristics at high angles of attack. A key feature for future models to be accepted will be rigorous uncertainty quantification not only of the aggregate model but also of its constituent components.

Paper 47.- This research was presented by P. RAJ and co-authored with D. B. FINLEY of the Lockheed Martin Aeronautics Company, and F. GHAFFARI of NASA Langley, **USA**. An assessment was presented of CFD effectiveness for vortex flow simulation to meet preliminary design needs for advanced fighter concepts. Euler-class technology was chosen for this assessment for two reasons. First, these vehicles often incorporate swept and relatively sharp edges that shed vortices dominant to both longitudinal and lateral-directional maneuver aerodynamics. Second, the preliminary design environment requires fairly rapid turn around for computations to be useful. Two very different configurations were studied at low speed and transonic conditions. Two Euler methods were selected for this study, and both were shown to provide useful force and moment estimates when compared to experiment for supporting preliminary design needs.

Paper 48.- H. A. GONZALEZ of the Naval Air Systems Command presented this research that was co-authored with G. E. ERICKSON of NASA Langley and B. G. MCLACHLAN and J. H. BELL of NASA Ames, **USA**. A $76^o/40^o$ double delta wing was used to experimentally study the effect of fillet planform shape (at the sweep discontinuity) on the vortex flow aerodynamics. Four different fillet shapes were tested in the NASA Langley 7x10 foot Tunnel for Mach numbers from 0.17 to 0.70. An extremely thorough suite of instrumentation technology was used for this study that included static surface pressure taps, pressure sensitive paint, six-component forces and moments, and off-body laser-vapor-screen flow visualization. As in the presentation from Paper #33, this diverse suite of measurements was used to present an extremely thorough understanding of a very complex and interacting vortex flow.

4.0 EVALUATION AND CONCLUSIONS

Separation induced vortex flows are pervasive to military vehicle aerodynamics and hydrodynamics, for the most part due to high angle-of-attack maneuver requirements. High speed and survivability requirements also contribute to vehicle shaping that is conducive to these flows. The papers of this symposium have provided a view toward the complexity of these flows along with their many ramifications for military vehicle aerodynamics and hydrodynamics. These collective findings also provide a benchmark for the status of experimental investigations, numerical studies, and design applications for separation-induced vortex flows.

These vortices are nonlinear off-body fluid structures that are connected to the spawning aerodynamic surface by a feeding sheet of vorticity. The vortices themselves contain local fluid extrema and persist along a-priori unknown trajectories in the overall flow; all of this occurs in the near field of the military vehicle. To add to the complexity, these vortices can undergo a change of state known as bursting or vortex breakdown (analogous to separation within a boundary layer) that can have deleterious consequences on vehicle aerodynamics. Nonetheless, separation-induced vortices are unavoidable for these vehicles, and in many cases can be exploited to meet multipoint performance and/or multimission requirements. Thus, the separation-induced vortex flow provides a unique challenge, not only to experimental and computational aerodynamics, but also to integrated vehicle design.

From a basic vortex flow physics perspective there are a number of fundamental challenges that are manifested from laboratory environment to flight. Vortex breakdown continues to be a most challenging phenomenon, but some excellent progress has been demonstrated for modeling and understanding this phenomenon with Navier-Stokes techniques for isolated vortices. There continues to be a need for detailed measurements of this flow, as well as implementation of numerical capability for configuration applications.

For the sharp leading-edge vortex flow there remain voids in our understanding of boundary-layer flows, boundary-layer transition, smooth-surface secondary separation, interaction effects between the primary and secondary vortices, and vortex breakdown. Detailed flow-field measurements continue to be useful for this flow. Practical wing design considerations produce swept leading edges with small but finite bluntness, and our ability to predict and manage vortex flows for this condition is inadequate for design purposes. Detailed experimental and numerical studies for vortex flows from blunt-edged delta wings need to be pursued. Because of the blunt leading edge, Reynolds number effects must be included. Projects like these are strong candidates for resource sharing through multinational collaboration.

Multiple co-rotating vortices from a single wing planform were encountered in a number of cases and appear to be more common than had been expected. It is not clear that the capability exists to predict the onset of these vortices or to model the interaction effects among them. This presents challenges for numerical and experimental aerodynamics as well as for wing design. One could envision a number of investigations, not only to study the strongly interacting vortices such as from a double-delta wing, but also to understand the weakly interacting vortices such as were encountered on the F-106B vortex flap or shown for a swept-wing UCAV concept.

With regard to test techniques, there has been encouraging use of pressure sensitive paints (PSP) for unsteady flow measurement. These measurements will need to be anchored with established unsteady pressure measurement techniques as confidence is built for the unsteady PSP technology. PSP also provides an excellent means of surface flow visualization to quantify the footprint of the separation-induced vortex flows. Off-body flow visualization, usually through a laser light sheet, also contributes significant understanding to these vortex flows. It would be desirable for this class of flow visualization to provide quantitative measures of the vortex trajectory and size. There has also been some encouraging use of Particle Imaging Velocimetry (PIV) to obtain fairly extensive off-body measurements of separation-induced vortex properties. One considerable issue, though, remains to be the measurement of the vortex core flow details. For typical wind-tunnel conditions it was demonstrated that any seeded particle would depart from the flow in the neighborhood of the core. Hence, alternate non-intrusive measurement technology will be required.

Some of the most noteworthy experimental investigations from this symposium exploited a diverse combination of measurement technologies focused toward understanding a specific vortex flow. This practice, however, is more the exception than the rule, and there is a need for future experiments of this type that are targeted toward the voids in our understanding of these flows and that can thereby further guide the development of computational technology and design concepts. Such experiments are often best performed with relatively simple geometries and are strong candidates for collaborative resource sharing.

Most of the experiments did not address accuracy or repeatability very much, and it was shown in one paper that there are examples of considerable scatter within the historical database (in this particular case, with regard to vortex breakdown location). It is recommended that more rigorous experimental uncertainty practices be adopted and modified as needed for experimental vortex flow studies. Guidance can be found among the works of Coleman and Steele (1989), Oberkampf and Aeschliman (1992), Hemsch (2000), as well as a number of other sources. This would lead to future testing practices that could resolve the vortex breakdown example just mentioned, and could also lead to the selection of some standard configurations, flows, and measurements from which to benchmark various facilities. Here again, such experiments are best performed with relatively simple geometries and through multinational collaboration.

There now seems to be a wealth of flight data that has been accumulated through a number of programs with multiple aircraft. Examples were shown for the F-18, the X-31, the F-106B, and the F-16XL-1. High angle-of-attack data are available for other aircraft as well (i.e., the X-29) that were not included in this symposium. This presents an excellent opportunity to use these data for a variety of vortex related analyses (flight characteristics, ground to flight scaling, correlation with CFD, etc.). A second challenge for the flight test community will no doubt be to pursue new maneuver flight-test data activities, such as for the new generation of vehicles designed for survivability (e.g., F-22, F-35). Compared to prior aircraft, these vehicles generate vortex flows that may differ significantly both in terms of flow features and airframe interaction effects.

Turning to computational aerodynamics, it now appears that Navier-Stokes methods are becoming highly utilized for predicting a variety of vortex flow effects. This must not be construed, however, to imply that the use of these methods is routine. Through careful computational studies, a number of papers assessed numerical effects in association with grids and turbulence models to arrive at proper or improved modeling of the particular vortex flow of interest. Grid resolution of these off-body vortices will continue to be a concern, but one study demonstrated very promising initial results from an adaptive unstructured technique to grid-resolve the vortices. This type of work is highly encouraged. All of this is a good initial step toward quantifying numerical uncertainty for computational vortex flow aerodynamics. It would be beneficial to address numerical uncertainty for vortex flow applications through a broad-scale collaboration. Critical data sets could be identified or requirements defined, and a coordinated effort performed to synthesize best practice procedures as regards algorithms, grids, turbulence models, and the like for a suite of vortex flows. Such an effort could benefit from multinational participation to achieve computational diversity and to distribute the workload.

Several unsteady CFD applications also demonstrated this to be an emerging capability for vortex flow applications. Hysteresis loops were predicted for unsteady delta wing motion, and unsteady blowing effects on a leading-edge vortex were also well simulated. A very effective use of unsteady Navier Stokes computation was demonstrated for initial estimates of a very complicated vortex flow associated with ship wakes. The unsteady formulation was vital to a reasonable correlation with full-scale ship data.

The maritime work was an excellent extension to this vortex flow symposium. Many similar issues and tools exist for the maritime and aircraft communities, and it is recommended that this extension be sustained for future vortex flow symposia. The maritime work demonstrated a very strong and explicit linkage between the research programs and customer interests or fleet issues. While the aircraft-motivated work was also of extreme relevance, this type of linkage was not as clearly enunciated, and this should be remedied.

Throughout the symposium there were some exceptional examples of flow analysis and physics-based reasoning in the development of analysis and/or computational tools. As one example, vortex breakdown effects were modeled in several papers to arrive at very good estimates of force and moment hysteresis loops. This type of approach allows for an inferential link to be established between the modeled physics (vortex breakdown) and the outcome metric (hysteresis loops). In general, this approach also produces very rapid computational tools as was shown for a modeling approach to cavity aerodynamics. Leading-edge suction concepts were exploited in several cases as well. This class of analysis is highly encouraged, as it can often add a level of understanding to a particular flow that is difficult to otherwise extract from isolated experimental or CFD studies.

This symposium also included a review paper from a very recent RTO symposium on flow control. It is reasonable to assume that many participants in the present vortex flow symposium were not also in attendance at the flow-control symposium, and yet there was a significant amount of material relevant to vortex flows. This type of cross-symposium communication was a very effective means to transfer knowledge among RTO participants and is encouraged for future RTO symposia.

This symposium was very worthwhile. Considerable progress was demonstrated in many aspects of vortex flows. At the same time, many challenges remain to be addressed for these flows that range from fundamental investigations to full-scale aircraft or maritime studies. From a design perspective, one may choose to exploit, to eliminate, or to tolerate the aerodynamic or hydrodynamic effects of separation-induced vortex flows. For any of these desires, however, one must be able to predict and understand the vortex physics with sufficient accuracy in order to control its influence on vehicle performance.

5.0 ACKNOWLEDGEMENTS

The Program Committee is acknowledged for taking all steps necessary to create this symposium. They are listed in Section 7. The author wishes to particularly thank Ms. Sandra Cheyne, AVT Panel Assistant, for all of her support.

6.0 CITATIONS

6.1 Symposium Program

- **KEYNOTE ADDRESS**
  Military Vortices
  D. LOVELL, DERA, UK

- **SESSION I: VORTICAL FLOWS ON WINGS AND BODIES**
  Chairman: D. LOVELL, UK

  1. Motion Effects on Leading Edge Vortex Behaviour Over Delta Wings and Generalised Modelling
     X.Z. HUANG, E.S. HANFF, National Research Council of Canada, Canada
  2. The Passage Toward Stall of Nonslender Delta Wings at Low Reynolds Number
     M. V. OL, Air Force Research Laboratory, Wright Patterson, USA
  3. An Experimental and Computational Study of the Aerodynamics of a Square Cross-Section Body at Supersonic Speeds
     T.J. BIRCH, G.M. SIMPSON, DERA, UK

- **SESSION II: EXPERIMENTAL TECHNIQUES FOR VORTICAL FLOWS**
  Chairman: J. LAMAR, USA

  4. An Experimental Study of the Flow Around an Axisymmetric Body Under High Angles of Attack
     D.K. PANTELATOS, D.S. MATHIOULAKIS, National Technical University of Athens, Greece
  5. Pitfalls in Interpretation of Delta Wing Vortex Flow Visualisation Images
     D.I. GREENWELL, DERA, UK
  6. Study of Unsteady Behavior of a Rotating 65° Delta Wing at M=0.8 Using Pressure Sensitive Paint (PSP)
     R. ENGLER, S. FONOV, C. KLEIN, K-A. BUETEFISCH, D. WEISKAT, German Aerospace Center, DLR Goettingen, K-W. BOCK, German-Dutch Wind Tunnels, W. FRITZ, EADS, Germany
  7. Transonic Pressure, Force and Flow Visualisation Measurements on a Pitching Straked Delta Wing at High Alpha
     A.M. CUNNINGHAM, Lockheed Martin Aeronautics Company, USA, E.G.M. GEURTS, National Aerospace Research Laboratory, The Netherlands
  8. A New Vortex Flow Experiment for Computer Code Validation
     D. HUMMEL, Technical University of Braunschweig, G. REDEKER, DLR, Germany

- **SESSION III: NUMERICAL SIMULATIONS OF VORTICAL FLOWS**
  Co-Chairs: N. MALMUTH, USA, T. CROSS, UK

9. Vortex Flow Dilemmas and Control on Wing Planforms for High Speed
   R.K. NANGIA, Nangia Aero Res. Associates, A.S. MILLER, BAe Systems Airbus, UK
10. Modèle aérodynamique instationnaire pour des ailes minces avec nappes tourbillonnaires issues des extremités et du bord d'attaque
    (Unsteady Model for Thin Wings with Evolutive Vortex Sheets Including Tip and Leading Edge Separation)
    A. LEROY, F. BURON, P. DEVINANT, University of Orleans, France
11. Time Accurate Euler Calculations of Vortical Flow over a Delta Wing in Rolling Motion
    W. FRITZ, EADS, Germany, M.T. ARTHUR, DERA, UK, F.J. BRANDSMA, NLR, The Netherlands, K.A. BUETEFISCH, DLR, Germany, N. CERESOLA, Alenia, Italy
12. Unsteady Separated Flows and Airfoil-Vortex Interactions
    M. MAMOU, H. XU, M. KHALID, National Research Council of Canada, Canada
13. Vortical Flow Prediction Using an Adaptive Unstructured Grid Method
    S. Z. PIRZADEH, NASA, USA
14. Leading Edge Vortex Flow Computations Using Full Reynolds-Averaged Navier-Stokes Equations With Two-Equation Turbulence Models, and Comparison With Flowfields Measured in HST Wind Tunnel
    F.J. BRANDSMA, J.C. KOK, H.S. DOL, A. ELSENAAR, NLR, The Netherlands
15. Numerical Simulation of Vortex Flows Around Missile Configurations
    P. CHAMPIGNY, D'ÉSPINEY, ONERA, M. BREDIF, H. BROUSSARD, Matra BAe Dynamics, J.P. GILLYBOEUF, Y. KERGARAVAT, EADS-Aerospatiale, France

- **SESSION IV: VORTEX STABILITY AND BREAKDOWN**
  Co-Chairs: D. HUMMEL, Germany, X.Z.HUANG, Canada

16. Axisymmetric and Non-Axisymmetric Initiation of Vortex Breakdown
    A.W. CARY, Washington University (St Louis), D. L. DARMOFAL, MIT, USA
17. A Critical Assessment and Requirement for Ground Testing on Vortex Breakdown Locations Over Delta Wings
    X.Z. HUANG, C.E. JOBE, E.S. HANFF, National Research Council of Canada
18. Normal Shock Vortex Interaction
    O. THOMER, E. KRAUSE, W. SCHROEDER, RWTH Aachen, Germany
19. Experimental Investigation of Vortex Breakdown over Delta Wings with Consideration of Control by Fluid Injection
    P. MOLTON, T. MITCHELL, D. BARBERIS, D. AFCHAIN,
    O. RODRIGEZ, J. PRUVOST, ONERA, France
20. Flow Control of Vortical Structures and Vortex Breakdown Over Slender Delta Wings
    A. MITCHELL, S. MORTON, USAF Academy, USA, P. MOLTON, ONERA, France, Y. GUY, Israeli Armament, Israel
21. Numerical Modelling of Vortex Flow Instabilities and Interactions
    M. MOKRY, National Research Council of Canada, Canada

22. Aerodynamics of Delta Wings at High Angle of Attack - Evaluation and Analysis of Numerical Simulation combined with CFD Simulation of a Delta Wing in High-Alpha Pitch Oscillation
    S. GOERZ, A. RIZZI, Y. LE MOIGNE, KTH, Sweden
23. Prediction par calcul de l'éclatement tourbillonnaire sur aile delta d'avion militaire
    (CFD Prediction of Vortex Breakdown on Delta Wings for Military Aircraft)
    J-P. ROSENBLUM, J-M. HASHOLDER, J-C. COURTY, Dassault Aviation, France

- **SESSION V: VORTEX FLOWS IN MARITIME APPLICATIONS**
  Co-Chairs : T. YTREHUS, Norway, P. PURTELL, USA

24. Marine Vortices and Their Computations
    J. J.GORSKI, Naval Surface Warfare Center, USA
25. A Computational Study of Unsteady Ship Wake
    S. A. POLSKY, C.W.S. BRUNER, Naval Air Warfare Centre, USA
26. Airwake Simulation of Modified TTCP/SFS ship
    C. T. TAI, US Naval Surface Warfare Centre, USA
27. A Quasi-Steady Evaluation of Submarine Rising Stability
    G.D. WATT, Defence Research Establishment Atlantic, Canada
28. Vortex Effects in the Dynamics of Underwater Weapons
    P.L. LYES, BAe Systems, P. STEER, DERA, UK
29. Physics Based Simulations of Reynolds Number Effects in Vortex Intensive Incompressible Flows
    K. SREENIVAS, D. HYAMS, X. WANG, B. MITCHELL, L. TAYLOR, D.L. WHITFIELD, Computational Simulation and Design Centre, USA
30. **withdrawn**

- **SESSION VI: VORTEX INTERACTIONS AND CONTROL**
  Co-Chairs: L. LEAVITT, USA, C. CIRAY, Turkey

31. Vapor Screen Determined Quantifiable Vortex Features of F-106B Airplane at Subsonic Speeds
    J. LAMAR, NASA Langley, USA
32. **withdrawn**
33. Effect of Various Shape Fillets on a 76/40 Double Delta Wing from Mach 0.18 to 0.7. Part 1: Baseline 76/40 Double Delta Wing
    H.A. GONZALEZ, Naval Air Systems Command, G.E. ERICKSON, B.G. MCLACHLAN, J.H. BELL, NASA, USA
34. Experimental and Numerical Investigation of Vortex Shedding of a Representative UCAV Configuration for Vortex Control
    T.A. GHEE, D.R. HALL, Naval Air Systems Command, USA
35. Aerodynamic Active Vibration Alleviation for Buffet Excited Vertical Tails
    G. BREITSAMTER, Technical University of Muenchen, Germany
36. Simulation of Wind-Induced Vortex Flow and the Effect on a Helicopter Structural Failure
    H. NOERSTRUD, University of Trondheim, A. OESTMAN, CFD Norway, Norway
37. PC Desktop Aerodynamic Models for Store Separation from Weapons Bay Cavities and Related Vortical Processes
    N. MALMUTH, Rockwell Science Center, J. COLE, Rensselaer Polytechnic Institute, USA, A. FEDEROV, V. SHALAEV, Moscow Institute of Physics, Russia, M. HITES, D. WILLIAMS, Illinois Institute of Technology, USA

- **SESSION VII: VORTEX DYNAMICS**
  Chairman: H. NOERSTRUD, Norway

38. Modèle de coefficients aérodynamiques instationnaires d' un avion à voilure delta aux grandes incidences
    (Model of Unsteady Aerodynamic Coefficients of a Delta Wing Aircraft at High Angle of Attack)
    L. PLANCKAERT, ONERA, France
39. Prediction of Flows about Forebodies at High Angle of Attack Dynamic Conditions
    C.P. VAN DAM, S. SAEPHAN, University of California,
    C.M. FREMAUX, T. DALBELLO, NASA, USA
40. On the Use of Vortex Flows for the Propulsion of Micro-Air and Sea Vehicles
    K.D. JONES, M.F. PLATZER, Naval Postgraduate School, USA

- **SESSION VIII: FLIGHT TESTING**
  Chairman: P. SACHER, Germany

41. X-31: The First Aircraft Designed for High AoA Manoeuvrability
    H. ROSS, EADS Military Aircraft, Germany
42. Comparison of X-31 Flight and Ground Based Yawing Moment Asymmetries at High Angles of Attack
    B.R. COBLEIGH, M.A. CROOM, NASA, USA
43. In-Flight Flow Visualisation - Results of the F-106B with a Vortex Flap
    J.M. BRANDON, J.B. HALLISSY, P.W. BROWN, J.E. LAMAR, NASA, USA
44. Cranked Arrow Wing (F-16XL-1) Flight Flow Physics with CFD Predictions at Subsonic and Transonic Speeds
    J.E. LAMAR, NASA, USA
45. Forebody Aerodynamics of the F-18 High Alpha Research Vehicle With Actuated Forebody Strakes
    D.F. FISHER, D. G. MURRI, NASA, USA

- **SESSION IX: VEHICLE DESIGN**
  Chairman: J. LAMAR, USA

46. Design Issues Associated with Full-Scale Application
    D.J. MOORHOUSE, Air Force Research Laboratory, WPAFB, USA
47. An Assessment of CFD Effectiveness for Vortex-Flow Simulation to Meet Preliminary Design Needs
    P. RAJ, D.B. FINLEY Lockheed Martin Aeronautics Company, F. GHAFFARI, NASA, USA
48. Effect of Various Shape Fillets on a 76/40 Double Delta Wing from Mach 0.18 to 0.7. Part 2: Fillet Effects
    H.A. GONZALEZ, Naval Air Systems Command, G.E. ERICKSON, B.G. MCLACHLAN, J.H. BELL, NASA, USA

SYMPOSIUM CLOSING CEREMONY

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J. LUCKRING, NASA, USA

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